AEC022

Researching Design and Fabricating Development of a Solar – Powered Stirling Engine-Generator

Sutapat Kwankaomeng[1,*], Banterng Silpsakoolsook[2], Pongnarin Savangvong[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Chalongkrung Rd., Ladkrabang, Bangkok, 10520, Thailand
[2] Department of Chemistry, Faculty of Science, Siam University, Phasichareon, Bangkok, 10160, Thailand
[*] Corresponding Author: E-mail address: kksudara@kmitl.ac.th, Tel: +66-2329-8351, fax: +66-2329-8352.

Abstract

Thailand locates in a tropical zone having average potential solar power of 18.2 MJ/m^2 per day. Since the solar energy is free and clean it is undeniable an attractive energy source ready for harvesting by suitable heat engines. This article proposes a design to build a heat engine, namely a Free-Piston Stirling Engine (FPSE) which can efficiently convert heat to work without crank mechanism. A prototype of FPSE was then constructed by the design in coupling with a solar collector and a generator. The FPSE, consisting of two pistons reciprocating by shuttled gas and mechanical springs acting as energy absorber or elastic bumper, was preliminary designed to operate under ambient air. Engine characteristics were investigated and simulated under Schmidt's assumption, i.e. isothermal hot and cold sections at heater and cooler, respectively. Both kinematic and kinetic parameters including spring constant were simultaneously solved by written MATLAB(R2010b) code to improve the FPSE efficiency and stability. Suitable spring stiffness as a result must be tuned for engine actuation which produced optimum operating conditions. The prototype was heated by electrical heater to simulate solar radiation and cooled by running tap water. The experimental results indicated that the built FPSE prototype had given promising power with piston and displacer mass of 145 and 162 g, respectively, at a low temperature range of 353-473 K with the displacer spring rate of 300 N/m, and the piston stroke range of 45-55 mm.

Keywords: Stirling engine, solar collector, parabolic dish, free-piston

1. Introduction

While the increasing population demands for unlimited energy consumption, we are inevitably continue facing oil pricing, global warming, and environmental polluting. Climate change as a result causes natural disasters more destructive and severe that hammers into energy usage problems of humanity. Due to high heating value of fossil fuel in any phases, this makes it a popular energy sources but its usage leads to an advert effect to our habitats due to greenhouse gas emission. This issue is now serious enough that reducing the CO_2 emission in all industrial sections becomes global agreements as constrained commercial issues by intercontinental exporting and importing products. To mitigate the troublesome, compensation or replacement of fossil fuel by alternative sources of energy has been seek by national laboratory all over the world with the objectives of longer fortunate livings and world protection.

Solar energy, thus, plays an important role as renewable and sustainable energy especially clean, free and available during day time. Hence solar hunting technologies are invented for efficiently extract such energy source as high as possible. Conventional techniques are solar panel or photovoltaic cell and solar tower gradually development but costly. However, modern solar panels are drastically cheap with material advancement using crystalline silicon and cadmium-telluride. It claimed by GTM research [1] that solar PV can be invested less than one dollar per one watt electricity.

Stirling engine, invented by Robert Stirling and patented in 1816 [2], is an optional engine that can be perfectly integrated with solar collector catching more power area density and effective cost compared to that of any solar conversion methods by modern solar Stirling engine. Primitive solar Stiring engine was firstly proposed by John Ericsson [2]. Niche market on solar powered Stirling engine is aggressive competition. Solar Stirling Energy System (SES) [3] and Infinia companies [4], once seems to have bright future breaking world record, launched solar driven Stirling engines catching more solar power by high performance Stirling engines with crank mechanism and free-piston structures, respectively. Even though, those companies planned to have a number of megawatt-projects but finally end up with bankruptcy in 2011 [5] according to lacking of enough financing and deceased by remarkable cost reduction of efficient solar panel.

Solar powered Stirling engine, nevertheless, is not yet done in technology instead continuing develop and came up with more impressive and undefeatable record by Ripasso Energy Company [6]. The company established world record solar to grid electricity of 32 %, Stirling engine efficiency over than 40 % without water utilization in the system and minimal area installation of 10000 m^2 for producing 1 MW. The system unit consists of 12 meter diameter collective dish with total mirror surface area of 104 m^2

and Stirling engine generating up to 33 kWe at 2300 rpm, maximum pressure and temperature operation of 20 MPa and 720°C consequently. System lifetime is over than 25 years with negligible degradation and long service interval which is much more improved than that of SES Company.

New version of free-Piston Stirling engine application introduced and marketed by Qnergy Company [7]. Micro-CHP was announced producing both heat and power by multi- fuel choices such as natural gas, biogas and biomass with long operation and maintenance free especially silence operation. The commercial free-piston Stirling engine was offered two scales of 3.5kWe for residential and 7.5kWe for business [7]. Since Thailand is located in equatorial region which is generally hot. This appliance, although, provides power and heat but excessive heat might be useless.

Researching design must be conducted in order to obtain optimal engine and efficient system. Wang and Siddiqui [8] shows simulated results of a solar collective dish dimension on thermal performance on the receiver and Argon as the working gas. Reduction in size of aperture from 0.05 to 0.025 m, enhances average temperatures on wall surface and Argon in the receiver of 7.5 and 9.2 %, consecutively. They concluded that rim angle of the solar dish has insignificant effect on thermal characteristics of the receiver while they recommended that Argon, the working gas, should be flowed in at the top to leave at the bottom of the receiver.

Kumar and Reddy [9] presents numerical study on convective heat loss from three cavities of receivers. The minimum heat loss could achieve with the optimal area ratio of 8. Shuai et al [10] also carried out calculated radiation performance and receiver characteristic with five concavity geometries by using Monte-Carlo method. Some insights on parabolic dish with convective heat loss from the receiver were summarized in a review of Wu et al [11]. Optimization of solar driven Stirling engine with regenerative heat loss was investigated by Arora et al [12]. They claimed that optimal values are benefit as bench mark for end user.

Although such Stirling engine system technologies presented are noticeable, there are still costly for investment with countless payback periods. Unaffordable price, furthermore, includes taxation and shipping making untouchable technologies. For these reasons, this paper is aimed to propose design and build a solar powered-Stirling engine generating electricity by utilizing local materials and manufactures. In order to develop and improve such a system applied in Thailand with cheaper and reachable for rural areas and off-grid services. Because Thailand, even though, has many solar power plants but electrical production can extract solar power just only 400 MW from available total solar power of 10 GW [13]. Heat dumped by Stirling engine, furthermore, could be used to preheat or reheat for those heat requirement systems or power plants as combined cycle power plants.

2. Design Methodology

There are two major parts to design and analyze consisting Stirling engine and solar collector to cooperate as heat engine and heat source. Solar collective dish functions as the heat collector for the engine by focus solar power on engine heater. Stirling engine is an external heat engine that converts heat rate to mechanical power. Generator, then, transforms mechanical to electrical power. Design of Stirling engine and solar collective dish are discussed as follow.

2.1 FPSE components

Stirling engine beyond crank mechanism structure is free piston pattern developed by Professor Beale [14] which gives more compact and less elements including self-starting possibility. The schematic of FPSE components are illustrated in Fig.1. The crucial parts comprise dynamic parts and heat exchangers. The moving elements are displacer and power piston and magnet piston assembly. All pistons are reciprocated freely under the limitation of springs. The challenging design of FPSE, therefore, is stiffness compatibility of compressible gas spring in the bounce space and mechanical spring as the displacer buffer.

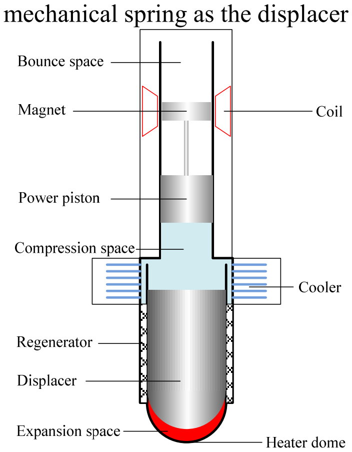

Fig. 1 Schematic of FPSE elements

The oscillation of working gas through the heater, regenerator, and cooler and vice versa, induces displacer and piston movements according to gas shuttles between heater and cooler because of gas expansion and contraction. When the heated gas is expanded in the expansion space, the displacer, then, is moved close to power piston enhancing more compression on the cooled gas to have enough force pushing on the piston to produce power from the FPSE. The power produced, hence, can be extracted to be useful power or electricity. During the displacer slides away from the expansion space pushing cooled gas flow through the regenerator and heater, respectively, gas is preheated and reheated. After the power piston has given the power stroke, the gas pressure is reduced resulting in displacer and the working piston were moved back by gas spring and bounce chamber, respectively, and initiated the new cyclic motion.

Without temperature difference of the working gas, Stirling engine could not be operated. Heater, regenerator and cooler are also critical parts that impact on engine efficiency. Heat source is absorbed by heater head. Regenerator acts as the heat storage, absorbed and preheated the working gas that is circulated between expansion and compression sections. Cooler is the heat sink that heat is rejected from the working gas to the coolant.

2.2 FPSE Analysis

The FPSE consists of two pistons reciprocating according to shuttled gas between expansion and contraction spaces. The displacer is loose fit along its cylinder and surrounded by the working gas in both hot and cold sections thus the gas pressure, P_w, assumed to be momently constant. Because free piston Stirling is operated without crank mechanism and flywheel, both displacer and power piston are sliding freely. Mechanical spring is placed on displacer rod as elastic bumper and energy absorber for stroke limitation and repeatedly cyclic activating purposes. While the power piston is attached to gas springs situated separately at cold and bounce spaces in form of pressure forces, P_w and P_b, on individual volume.

Engine analysis was performed by using equation of motion, ideal gas equation, and Stirling cycle thermodynamics including instantaneous isobaric and isothermal hot and cold space assumptions. Kinematic parameters include displacement (x), velocity ($\dot{x}$), and acceleration ($\ddot{x}$) of dynamic elements obtained by solving equations of motion on the displacer and the piston assembly depicted in Fig.2 of their free body diagrams. Equations of motion are derived and rearranged as in Eq. (1) where K and D are stiffness and damping coefficient matrixes.

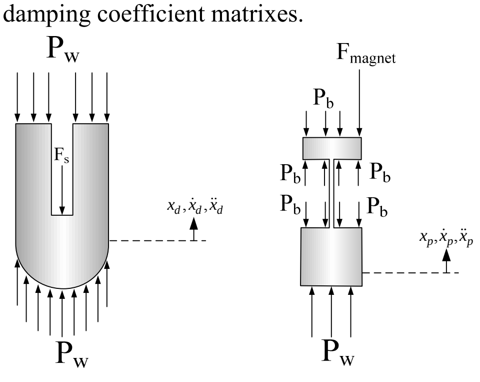

Fig. 2 Free-body diagram of displacer and piston assembly

$$\begin{bmatrix} \ddot{x}_p \\ \ddot{x}_d \end{bmatrix} = [K]\begin{bmatrix} x_p \\ x_d \end{bmatrix} + [D]\begin{bmatrix} \dot{x}_p \\ \dot{x}_d \end{bmatrix} \quad (1)$$

Because engine is assumed to be heated and cooled under steady state condition, expanding and contracting temperatures at hot and cold sections consecutively are maintained to be constant as Schmidt's assumptions. Based on Schmidt's analysis and harmonic movement assumption of displacer and piston, volume and pressure are defined by Eqs.(2)-(4).

$$V_e = \frac{V_{se}}{2}(1+\cos(\omega t-\varphi)) + V_{de} \quad (2)$$

$$V_c = V_{se} - \frac{V_{se}}{2}(1+\cos(\omega t-\varphi)) + \frac{V_{sc}}{2}(1+\cos(\omega t)) + V_{dc} \quad (3)$$

$$p = MR\left(\frac{V_c}{T_c} + \frac{V_{dc}}{T_c} + \frac{V_r \ln(T_h - T_c)}{T_h - T_c} + \frac{V_e}{T_h} + \frac{V_{de}}{T_h}\right) \quad (4)$$

Matlab codes are written to simulate engine characteristics. Parameters and operating conditions for simulation are shown in Table 1. Engine is initially charged with atmospheric air as the working gas. The hot and cold reservoirs exchange heat through the heater and cooler resulting gas temperatures of 180 and 40 °C, consecutively. The oscillating strokes of displacer and piston are limited 30 and 70 mm, respectively.

Table. 1 Parameters input for engine analysis

Displacer mass	162 g
Piston mass	145 g
Displacer cylinder diameter	48.5 *mm*
Working piston/ cylinder diameter	27.0 *mm*
Displacer diameter	47.0 *mm*
Displacer rod diameter	6.0 *mm*
Displacer stroke	30.0 *mm*
Piston stroke	70.0 *mm*
Hot space temperature	180°C
Cold space temperature	40°C
Working fluid	Air
Initial Pressure	1 atm
Engine speed	7.5 Hz
Phase angle	90°

From numerical results, the displacements of displacer and piston are sinusoidal. The power piston displacement lags after that of displacer with phase angle of 90 degree. Pressure and volume variation is illustrated in Fig. 3. The maximum and minimum pressures of air are 226.46 and 117.16 kPa, respectively. Work can be determined from area of enclosed PV loop of 1.18J/cycle and divided by period deriving power of 8.4 W.

Optimal spring stiffness is evaluated at the variation of operating pressure and temperature as represented in Fig.4. Routh-Hurwitz stability method was used to analyze stability operation of the engine. The extreme value of spring rate computation satisfying stable condition is 302 N/m. With such optimum spring constant, the trajectories of displacement and velocity relationship on phase diagram which reveals stabilized motion of displacer and power piston presented in Figs. 5-6, respectively.

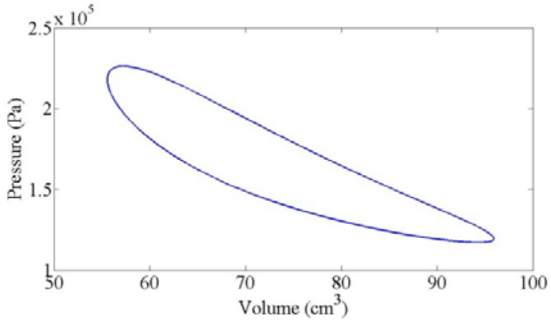

Fig. 3 PV diagram with Schmidt's analysis

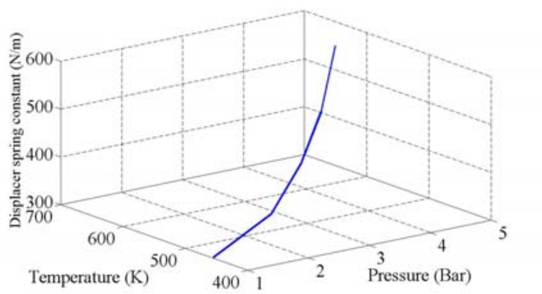

Fig. 4 Optimal spring constant acting on displacer under operating pressure and temperature

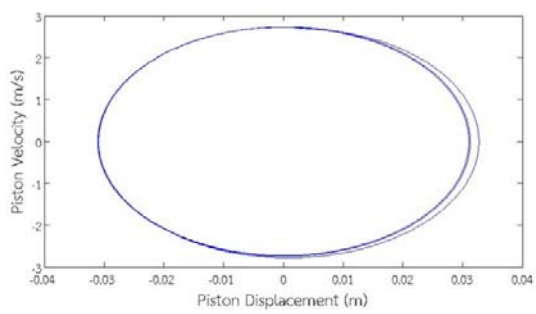

Fig. 5 Relationship of piston's displacement and velocity under stabilized oscillation

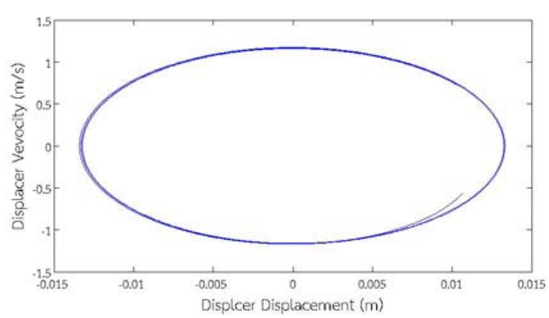

Fig. 6 Relationship of displacer's displacement and velocity under stabilized oscillation

2.3 Solar parabolic dish and Analysis

Solar light is focused and concentrated at the focal point or line by solar collector. Typically, there are three unique patterns of solar collector such as parabolic dish, parabolic trough and solar tower (central receiver). The parabolic reflector, however, perfectly provides concentrated heat. The solar parabolic dish, hence, is suitable for design as the heat source of the FPSE. Solar driven Stirling engine system, therefore, comprise of the parabolic dish and Stirling engine with aperture situated on engine receiver as schematized in Fig. 7.

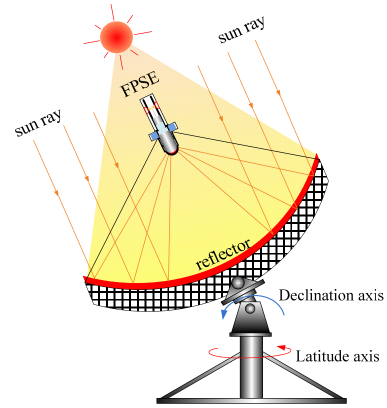

Fig. 7 Schematic of FPSE and solar dish system

In order to have highly concentrated solar power on engine's heater, the aperture area should be small giving large heat flux transfer to the engine. Hence concentration ratio and aperture area are considered. Kumar and Reddy [9] recommended the optimal area ratio of 8 for minimal heat loss.

In order to tracking the sun, the Zenith angle (θ_z) and Azimuth angle (γ) were calculated from Eqs. (5)-(6).

$$\theta_z = \cos^{-1}(\sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega) \quad (5)$$

$$\gamma = \sin^{-1}\frac{\cos\delta\sin\omega}{\sin\theta_z} \quad (6)$$

Where δ is the declination angle, ϕ is latitude angle and ω is hour angle.

3. Prototype and Experimental Set up

3.1 FPSE prototype and Set up

The prototype engine specifications are also described in Table 1. The engine and experimental instruments were schematized and equipped as illustrated in Figs. 8 and 9, respectively. Figure 8 shows schematic of engine integrated circuit devices. Firstly, the electric heater is applied heat to engine when the timer is on while cooling water pump is also operated. When the heater surface is heated up about 3 minutes, the DC circuit is then switched on thus current is discharged to the wiring coil generating magnetic field that initially activates the magnetic piston to move then the engine is started to run. After the engine operation is reached steady motion or stable running. The first LED is turned on as load applied on the engine, then voltage, current, and frequency are recorded. More LEDs are consecutively applied until the engine was stopped.

Figure 9 represents engine with equipment. The engine was heated by electrical heater of 200 W and cooled by water. UT-30C digital multi-meters were used as ammeter and voltmeter. A UN-860C multi-meter was also used to measure frequency of the engine's oscillation. A FLUKE 62MAX+ infrared thermometer was used to detect temperature of heater dome surface. The LED circuit was used as load.

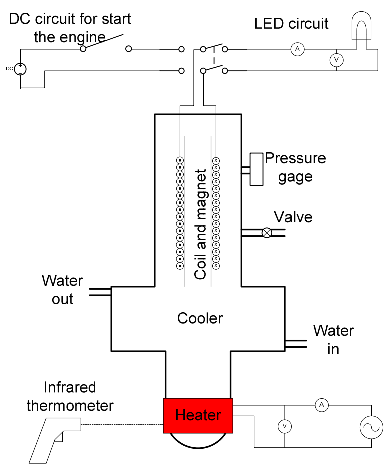

Fig. 8 FPSE with circuit devices

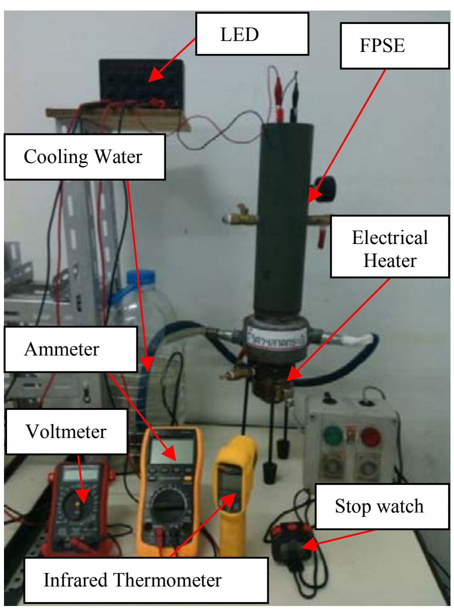

Fig. 9 The FPSE's test equipment

3.2 Solar parabolic dish and Set up

The solar dish system is showed in Fig. 10. The dish frame was made from D-SAT parabolic dish. The reflectors were made of aluminum anodize due to its flexibility and high reflectivity. The parabolic dish has an effective diameter of 1.5 m, depth of 0.25 m and focal spot of 0.56 m. The tracking system is used to trace the sun in order to get optimal incident light yielding highest intense heat at the focal point.

Tracking system consists of microcontroller system including global positioning system (GPS) and DC motor set. When location of the solar dish is known by GPS, the microcontroller then computes the sun position and control the DC motor to adjust the parabolic dish. To achieve the optimal position, the encoder is utilized to detect present position of the collector and also send it to microcontroller to compare the current position with desired position for mechanism arrangement. Thermocouples were placed to measure temperature values on the receiver at focus point, collector surface and ambient air.

Fig. 10 Solar dish with tracking system

4. Results and Discussion

4.1 FPSE Characteristics

The FPSE and solar collective dish were designed and built. The prototypes, however, were preliminary tested separately in order to verify their performances and further develop. The FPSE prototype, using ambient air as the working gas and water as coolant, was found the suitable operating conditions when using electric heater of 200 W. The engine can be started to run when the heater surface was gained enough heat until the temperate of 80°C. The steady or stable engine operation, can be achieved when the heater temperature was ranged between 120 and 180 °C. The power piston in the engine, however, is freely reciprocated but limited by bounce space as the buffer thus oscillated in the frequency interval of 7.3-7.8 Hz.

Power were evaluated with frequency variation and plotted in Figs. 11-13 under different piston stroke limitation of 45-55 mm. The power distributions in such figures reveal that engine with different piston stroke limitation has an optimal power at specific speed. The fitting curves of power variations over speed at stroke of 45, 50 and 55 mm were compared in the Fig. 14. The engine with longer piston stroke, the lower reciprocating frequency presented. The best piston stroke was about 50 mm. Even though, engine power seems insignificant value according to preliminary observation with imperfect methodology of instrumentation, the prototype will be pressurized in order to obtain optimal performance for additional development.

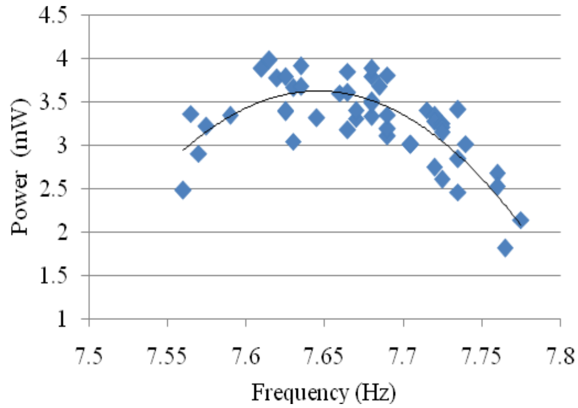

Fig. 11 Power with frequency with limited piston stroke of 45 mm

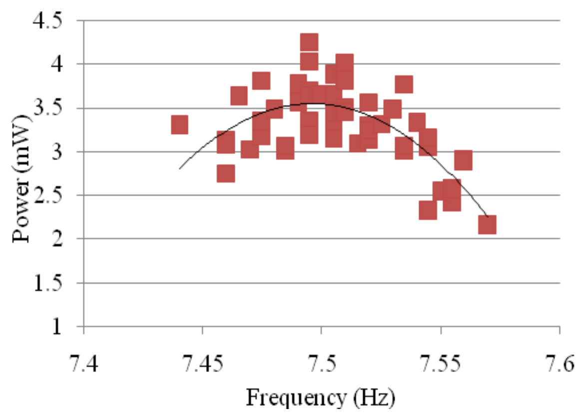

Fig. 12 Power with frequency with limited piston stroke of 50 mm

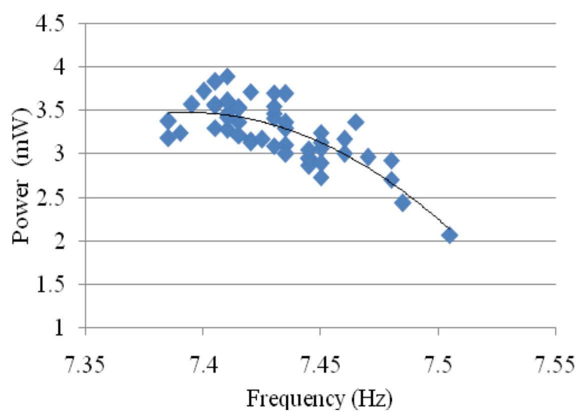

Fig. 13 Power with frequency with limited piston stroke of 55 mm

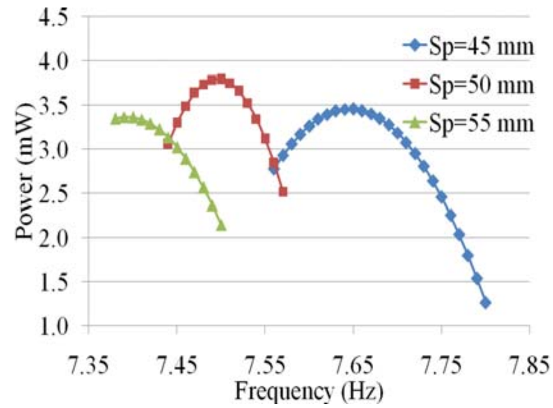

Fig. 14 Power against frequency of fitting curves with limited piston stroke (Sp) of 45-55 mm

4.2 Solar parabolic dish performances

The solar parabolic dish was tested and measured the maximum obtainable temperature during day time. The statistical data were collected during clear sky and calm weather. The average highest temperature was typically obtained at noon time during 12.00-2.00 pm approximately 450°C. The heat rate of 160 W at the focal point was evaluated by water boiling test. Even though solar power received highly depends on climate such as cloudy and windy besides convection heat loss, the engine however can be operated even at the low temperature of 353-473.

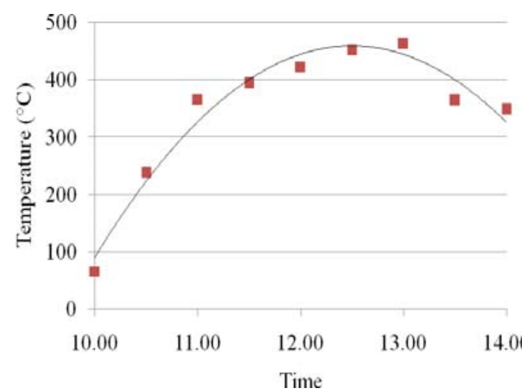

Fig. 15 Average focal temperature of solar parabolic dish

5. Conclusions

The FPSE characteristics were investigated both theoretical analysis and experimental test. The optimal stiffness of mechanical spring, key component for piston oscillation, was simulated and agreed with that of practical used 300 N/m. The solar parabolic dish was evaluated heating temperature and power received. Even though the engine and solar collector were preliminary proved separately in order to fulfill the optimal performance development before assembling, the testing results reveals that the parabolic dish can be used as the heat source for the engine even at low temperature of 353-473K. Next progress, engine will be run and improved by using pressurized helium as the working gas. Solar collector will be evaluated efficiency by comparing with measured solar intensity then the solar driven FSPE system will be validated.

6. Acknowledgement

The financial support of this research from the Office of the Higher Education Commission of Thailand (OHEC) is gratefully acknowledgement.

7. References

[1] Shyam Metha (2012). *PV Production, Technology and Cost Outlook: 2012-2016*, GTM research, USA, URL:http://www.greentechmedia.com/research/report/pv-supply-2012, accessed on 10/10/2015
[2] Walker G. (1980). Stirling Engines, Oxford, Clarendon Press.
[3] Solar Stirling Energy System, Inc (2015), *Power of Dish-Stirling Engine,* Scottsdale, AZ, USA, URL: http://graphiquecreative.com/clients/SES/contact.htm, accessed on 15/10/2015
[4] Qnergy company brochure (2015), Ogden UT, USA, URL: http://www.qnergy.com/sites/Qnergy/UserContent/filef/Qnergy_A4x3_v12.pdf, accessed on 15/10/2015
[5] Eric Wesoff (2013). *Rest in Peace: The List of Deceased Solar Companies,* GTM research, USA, URL:http://www.greentechmedia.com/articles/read/Re Re-in-Peace-The-List-of-Deceased-Solar-Companies, accessed on 15/10/2015
[6] Eric Wesoff (2013). *Another solar technology casualty-crushed by c-Si and CdTe*, GTM research, USA,URL:http://www.greentechmedia.com/articles/read/rest-in-peace-the-list-of-deceased-Solar companies, accessed on 15/10/2015
[7] Qnergy company brochure (2015), Ogden UT, USA, URL: http://www.qnergy.com/sites/Qnergy/UserContent/filef/Qnergy_A4x3_v12.pdf, accessed on 18/10/2015
[8] Mo Wang and Kamran Siddiqui, (2010). The impact of geometrical parameters on the thermal performance of a solar receiver of dish-type concentrated solar energy system, *Renewable Energy,* vol.35(11), November 2010, pp. 2501-1513.
[9] N. Sendhil Kumar and K.S Reddy (2008). Comparison of receiver for solar dish collector system, *Energy Conversion and Management*, vol.49(4), April 2008, pp. 812-819.
[10] Yong Shuai, Xin-Lin Xia and He-Ping Tan (2008). Radiation performance of dish solar concentrator/cavity receiver systems, Solar Energy, vol.82(1), January 2008, pp. 13-21.
[11] Shuang-Ying Wu, Lan Xiao, Yiding Cao and You-Rong Li (2010). Convection heat loss from cavity receiver in parabolic dish solar thermal power: A review, Solar Energy, vol.84(8), August 2010, pp. 1342-1355.
[12] Rajesh Arora, S.C. Kaushik, Raj Kumar and Ranjana Arora (2016). Multi-objective thermo-economic optimization of solar parabolic dish Stirling heat engine with regenerative losses using NSGA-II and decision making, *International Journal of Electrical Power & Energy Systems*, vol.74, January 2016, pp. 25-35.
[13] Chapter 10: Growth of Solar power plant in Thailand.URL:http://www.egco.com/th/energy_knowledge_solar10.asp accessed on 15/10/2015
[14] G.Walker (1973), Stirling-cycle machines, Oxford, Clarendon Press.

Nomenclature

D	damping coefficient
K	spring constant
M	mass of working gas (kg)
p	working gas pressure (Pa)
R	gas constant (kJ/kg-K)
T	temperature (K)
t	time(s)
V	volume (m^3)
x	displacement (m)
$\dot{x}$	velocity (m/s)
$\ddot{x}$	acceleration (m/s^2)
(θ_z)	Zenith angle (degree)
(γ)	Zenith angle (degree)
δ	declination angle (degree)
ϕ	latitude angle (degree)
ω	hour angle (degree)
Subscript	
c	compression space
d	displacer
dc	dead volume in compression space
de	dead volume in expansion space
e	expansion
p	Piston
r	Regenerator
sc	Swept volume in compression space
se	Swept volume in expansion space